Authoring Object-Bound Haptics: A Taxonomy of Workflows for Engineering Tactile and Kinesthetic Behavior

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Abstract

Haptic experiences in physical artifacts emerge not only from programmable effects, but also from artifact-specific properties such as geometry, materials, mechanical structure, physical configuration, and embedded actuation. We introduce object-bound haptics as a framing for this complementary space and define object-bound haptic authoring as the processes through which such tactile and kinesthetic behavior is specified, realized, evaluated, and refined. Relevant work is distributed across haptics, digital fabrication, tangible interaction, computational design, and engineering, and is rarely considered as a coherent authoring problem. To characterize this space, we review 51 papers and analyze its authoring workflows. From this corpus, we develop a taxonomy describing primary research focus, haptic target, and the sequence of digital and physical authoring, realization, and evaluation stages. Our analysis reveals a predominantly strong support for moving from digital representations to physical artifacts, comparatively limited support for transferring realized haptic behavior back into digital authoring, and a reliance on visual inspection and direct physical try-out for evaluation. We further synthesize recurring workflow structures into a unified model of object-bound haptic authoring.

CCS Concepts

• **Human-centered computing → Haptic devices**; **HCI theory, concepts and models**; • **General and reference → Surveys and overviews**.

Keywords

object-bound haptic authoring, digital fabrication, tangible modeling, prototyping, authoring workflows, taxonomy

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1 Introduction

Touch is central to how people experience physical artifacts [46]. The roughness of a surface, the softness of a material, the resistance of a slider, the snap of a latch, the weight of a prop, or the shape of a graspable object can determine whether an artifact feels usable, convincing, safe, expressive, or high quality. These tactile and kinesthetic qualities are not merely by-products of physical design. In many interactive artifacts, they are part of the intended user experience. Yet haptic qualities can be difficult to author [54, 57, 62]. Unlike visual properties, they are not fully captured by what an artifact looks like on screen [30]. Characteristics such as stiffness, friction, force, mass, texture amplitude, material distribution, or mechanism geometry can only be partially represented through traditional digital representations, such as parameter values, graph plots, or 3D renderings. As a result, studies of haptic design practice [57, 62] describe designers moving between digital models, simulations, physical prototypes, fabrication settings, and real-world testing to evaluate and refine intended haptic behavior.

Prior taxonomies [54] on haptic authoring have largely focused on programmable haptic output devices, such as vibrotactile actuators, force-feedback devices, wearables, or mid-air haptics. We refer to this traditional style of haptic authoring as *haptic-effect authoring*. These systems allow for authoring and testing haptic effects by composing timelines [11, 25, 69, 73], keyframes [28, 58, 59], libraries [10, 61, 63, 87], procedural models [5, 37, 70], and increasingly natural-language interfaces [38, 66].

A complementary body of work instead foregrounds the physical artifact and the properties through which its haptic behavior emerges. This work is distributed across engineering, digital fabrication, tangible interaction, virtual reality, and computational design, and is often not explicitly framed as haptic research. Engineering has long treated properties such as stiffness, friction, compliance, tolerance, material composition, and mechanism geometry as editable design variables, while advances in digital fabrication, HCI, and rapid prototyping have made such properties increasingly accessible as variables for designing felt experience [6, 15, 18, 27]. In these systems, haptic behavior is authored not only by programming an actuator signal, but by changing, for example, geometry, material composition, fabrication parameters, mechanical structure, physical configuration, and embedded actuation. We refer to this broader body of work as *object-bound haptics*: haptic behavior that is intentionally realized through *artifact-specific properties*.

In physical artifacts, physical properties shape both functional performance and felt experience. We focus on approaches that make intended tactile and kinesthetic behavior an explicit design concern. Bringing these approaches together allows us to examine

how haptic intent is translated into physical design choices, and how the resulting behavior is evaluated and refined.

Object-bound haptic authoring can pose a particular workflow challenge because the intended haptic behavior often becomes fully experienceable only after the artifact has been physically realized [57, 62]. Authoring may therefore require repeated movement between digital representations, fabrication or construction, physical evaluation, and subsequent refinement. These practices are distributed across several research communities and are rarely considered together as haptic authoring.

To understand how object-bound haptic behavior is authored, realized, evaluated, and refined, we focus specifically on *object-bound haptic authoring workflows* reported in the research literature as a common lens through which otherwise heterogeneous authoring methods can be compared. While authoring workflows for haptic effects have previously been systematically characterized [54], comparable understanding is lacking for object-bound haptics. Examining workflows captures not only how haptic intent is specified, but also how designs move between digital and physical representations, become physically experienceable, and are evaluated and refined. A workflow-level taxonomy couples what is authored with how digital and physical stages are sequenced, making systems from different communities comparable and unsupported transitions visible. Systematically analysing and cataloguing these workflows across research communities allows us to identify recurring authoring strategies, patterns of digital and physical iteration, and underexplored methods or potential gaps in current authoring support for object-bound haptics.

We therefore ask: *How does existing research support the authoring of object-bound haptic qualities, and what recurring targets, workflows, and tooling approaches characterize this work?*

We make these contributions. First, we introduce object-bound haptic authoring as a framing for unifying work across digital fabrication and mechanism engineering on the one hand, and haptic research on the other hand. Second, through a structured cross-disciplinary review and analysis of existing object-bound haptic authoring approaches, we develop a taxonomy that characterizes recurring authoring workflows and how haptic behavior is specified, physically realized, evaluated, and refined. The taxonomy enables comparison at the workflow level and exposes unsupported digital-physical transitions. Third, we use this synthesis to identify recurring challenges and opportunities for future object-bound haptic authoring and for closer integration with haptic-effect authoring.

2 Object-Bound Haptics within the Haptic Authoring Landscape

Building on the distinction of the two haptic authoring approaches, we use *haptic-effect authoring* to refer to approaches that primarily foreground a renderable haptic effect and the representations or parameters through which that effect is specified. This space has been systematically characterized in prior work [54]. We use *object-bound haptic authoring* to refer to the processes and tools through which artifact-specific tactile or kinesthetic behavior is intentionally specified, manipulated, physically realized, evaluated, and refined. We use *object* broadly to include physical and hybrid artifacts, object parts, surfaces, material samples, mechanisms, props, proxies, and assemblies. We reserve the term for work in which felt behavior is an explicit design concern rather than an incidental consequence of designing a physical object.

The two orientations overlap and should not be understood as active versus passive haptics. Object-bound artifacts may contain active components, while programmable haptic devices may be used to preview behavior [81] that is later realized through fabricated materials or mechanisms. Nor does the distinction separate virtual from physical applications, since both orientations occur in either setting [45, 57]. The distinction instead concerns what is treated as part of the authored haptic system. Haptic-effect authoring foregrounds a renderable effect and its parameters, while object-bound haptic authoring additionally foregrounds the artifact-specific properties through which the behavior is physically realized.

This difference also shapes the authoring process. Haptic-effect authoring has explored expressive and higher-level representations, rapid replay, and reusable effects across interactions or renderers. Object-bound authoring often requires manipulating geometry, materials, mechanisms, fabrication, or physical configuration. Because evaluating or changing these properties may require physical adjustment or fabrication, iteration can be more costly and the sequencing of digital and physical authoring stages becomes particularly important.

We therefore examine object-bound haptic authoring as a coherent authoring problem, complementing existing accounts of haptic-effect authoring by characterizing how artifact-specific haptic behavior is specified, physically realized, evaluated, and refined.

Concrete examples clarify this distinction. In HapticPrint [71], designers modify surface geometry and internal structure to shape the texture, compliance, and weight characteristics of a physical artifact. The artifact's physical construction is therefore part of the authored haptic system. By contrast, Macaron [59] specifies vibration intensity and frequency over time for playback through an existing actuator. The authored result is a renderable effect. Embedded actuation is possible for object-bound haptics as these may change the structure of the object itself. In Shifty [86], the mechanism and movable mass are engineered as part of the physical proxy, allowing actuation to change its mass distribution and resulting kinesthetic behavior.

3 Related Work

Our work builds on two bodies of literature: research on haptic perception and object properties, and prior work on haptic authoring and classification.

3.1 Haptic Perception and Object Properties

Haptic perception involves actively exploring physical properties of objects through touch and movement. Lederman and Klatzky [33] distinguish substance-related properties such as texture, hardness, and weight, structure-related properties such as shape, and functional properties such as part motion. ISO 9241-910 [21] similarly distinguishes geometric and material properties within tactile and kinesthetic interaction. These accounts provide a perceptual basis for the haptic targets used in our taxonomy, but do not address how

such properties are specified, physically realized, evaluated, and refined during authoring.

3.2 Haptic Authoring and Existing Taxonomies

Existing haptic classifications organize systems according to perceptual or interaction roles [9, 31], technology and physical realization [4, 53], or the fidelity of the resulting feedback [44]. These frameworks characterize what haptic systems produce and how their output can be understood, but generally do not capture the authoring process through which a desired haptic behavior is created.

Research on haptic authoring more directly examines this process. Studies of haptic practice describe recurring design activities and challenges [57, 62], while Regimbal et al. [54] characterize authoring tools according to dimensions such as hardware, design approach, interface, and playback. This work primarily concerns haptic effects rendered through programmable output technologies. Such systems often support rapid iteration between specification and physical playback, while object-bound haptic authoring additionally requires the artifact-specific geometry, materials, mechanisms, or physical configuration through which the behavior is realized.

Adjacent fabrication research examines how designers move between digital representations and physical artifacts [52], but does not organize these workflows around their intended haptic outcomes. Our work therefore complements both perspectives by characterizing object-bound haptic authoring as a complete workflow spanning specification, digital and physical representations, physical realization, evaluation, and refinement. Compared with existing classifications, which describe what haptic systems produce or which authoring tools exist, our taxonomy classifies complete workflows by what is authored and how digital and physical stages are sequenced, which allows comparing systems at the workflow level and locating unsupported transitions. This allows systems from haptics, fabrication, and tangible interaction to be compared on common terms, and reveals where digital and physical stages are well connected and where transitions or forms of evaluation are poorly supported, patterns that tool- or output-centred classifications cannot expose.

4 Review and Taxonomy Development

To develop a taxonomy grounded in existing object-bound haptic authoring practice, we conducted an interpretive review of relevant systems and authoring workflows. The review served two purposes: to construct a broad corpus that captures object-bound haptic authoring across research communities, including work that is not explicitly framed as haptic research, and to identify recurring authoring dimensions and workflow structures through iterative coding.

4.1 Scope and Inclusion Criteria

We operationalized the scope of the review using the definition of *object-bound haptic authoring* introduced in Section 2. We included contributions that intentionally support the authoring or engineering of haptic behavior through properties of a physical or hybrid artifact.

We include a contribution when it meets the following criteria:

(1) The intended haptic outcome is bound to a physical or hybrid artifact, such as an object, object part, mechanism, surface, material configuration, or proxy, rather than being rendered solely through a general-purpose haptic output device.
(2) One or more artifact-specific properties are intentionally treated as design variables that meaningfully contribute to the haptic outcome. These properties may include geometry, material composition, surface structure, mass distribution, mechanical behavior, assembly, physical configuration, fabrication parameters, or embedded actuation.
(3) The work contributes, describes, or exposes an authoring or engineering workflow through which the object-bound haptic behavior is specified, manipulated, predicted, physically realized, evaluated, or refined.

These criteria require the haptic behavior of the artifact to be an explicit design concern rather than an incidental consequence of designing a physical object. General-purpose CAD modelling, fabrication, or engineering work is therefore not included solely because the resulting object can be touched or because its physical properties may influence the user experience. This boundary is particularly important for haptic aspects involving shape, since the geometry of an object can be experienced both visually and through touch and manipulation. We include shape-oriented work only when the physically perceived shape is intentionally treated as a tactile or kinesthetic outcome, which we later refer to as *felt shape / form*. HapTwist [89] and StrutModeling [35] therefore fall within scope as their resulting geometry is explicitly considered in terms of how the object is physically experienced. In contrast, general-purpose CAD systems [75] are excluded.

A system can contribute an object-bound haptic artifact without exposing how its haptic behavior is authored. Snake Charmer [2] uses a robotic arm to position textured physical surfaces at the location of virtual objects, so that users can touch them in VR. It contributes an object-bound haptic system, the textured surfaces, but does not present an authoring system for them, and is therefore not aligned with our inclusion criteria.

4.2 Corpus Construction

We followed a literature review process with interpretive coding [78] and began by constructing a broad corpus of systems, tools, and workflows concerned with authoring object-bound haptics. Literature discovery took place between 2024 and August 2026, without restrictions on publication year. An initial scoping phase across haptic authoring was used to identify established work, relevant terminology, and the boundaries between object-bound authoring and haptic effect authoring. We expanded this initial collection through Google Scholar and ACM Digital Library searches, iteratively broadening the search vocabulary with terminology encountered in relevant publications. This included terms describing haptic qualities, artifact types, authoring activities, and realization methods, which subsequently informed the structured searches described below. Because relevant contributions are distributed across haptics, fabrication, tangible interaction, virtual reality, and mechanical design, and frequently do not describe themselves as haptic-authoring research, we subsequently used similarity-based

exploration and backward and forward citation searches. Using ResearchRabbit, we explored publications related to the seed papers and their citation networks, assembling approximately 942 candidate records. Titles and abstracts were examined to identify potentially relevant contributions. We also manually browsed proceedings from selected haptics, HCI, fabrication, and virtual-reality venues, including *ACM CHI*, *ACM UIST*, *ACM TEI*, *ACM DIS*, *ACM MUM*, *ACM VRST* and *ACM SCF*.

Finally, we conducted structured searches in the ACM Digital Library and IEEE Xplore by combining terms describing the intended haptic quality, the type of physical artifact, the authoring activity, and the method used to realize the artifact. These terms included *haptic*, *tactile*, *kinesthetic*, *texture*, *stiffness*, and *compliance*; *object*, *proxy*, *material*, *surface*, and *mechanism*; *authoring*, *design*, *prototyping*, *tuning*, *optimization*, and *inverse design*; and *digital fabrication*, *3D printing*, *multi-material fabrication*, and *compliant mechanisms*. Retrieved results were screened against the inclusion criteria described above. Given the interdisciplinary nature of object-bound haptic authoring and the varying terminology used across research communities, we combined structured database searches with purposive literature discovery [1, 67] through citation-network exploration and targeted venue browsing. Records were screened by title and abstract against the inclusion criteria, followed by full-text assessment of potentially eligible publications. Publications retained after this initial screening were subsequently assessed in full against the inclusion criteria.

Our literature search identified 2,150 records through ResearchRabbit (n = 942), structured database searches (n = 1,162), and supplementary citation and venue searches (n = 46). After removing 263 duplicates, 1,887 unique records underwent title and abstract screening, of which 1,705 were excluded. The remaining 182 publications were assessed in full against our inclusion criteria. Of these, 131 were excluded because they did not meet the criteria for object-bound haptic authoring. The final corpus comprised 51 papers, from which we identified 56 distinct authoring workflows.

The resulting corpus comprised 51 papers on object-bound haptic authoring. Most contributions appeared during or after 2010, consistent with the broader growth of haptic-authoring research reported by Regimbal et al. [54]. Our search focused on haptics, HCI, fabrication, and virtual-reality literature. The corpus therefore does not fully capture practice in domains where haptic quality has long been engineered, such as automotive interiors [32, 72], which we did not systematically consider.

4.3 Coding and Analysis

Object-bound haptics authoring workflows formed our unit of analysis. Each paper in our corpus presents at least one workflow. We coded multiple workflows for a single paper when the work exposed substantially different authoring processes, either for the same haptic outcome or for different outcomes. Conversely, when several haptic qualities were addressed through the same underlying authoring process, we treated these as a single workflow.

The corpus was analyzed through several stages of iterative qualitative coding. One author first conducted open coding on a subset of 17 contributions. This stage identified provisional codes for recurring authoring activities and workflow elements, including parameter editing, demonstration of target haptic intent, simulation, optimization, fabrication, physical configuration, embodied testing, and post-fabrication fine-tuning of haptic results. The authors then collectively reviewed the initial codes, consolidated overlapping concepts, clarified distinctions, and developed a shared codebook.

After establishing the codebook, one author performed focused coding across the complete corpus. During coding, cases that did not fit the existing scheme were discussed, the codebook was iteratively refined, and previously coded contributions were revisited to maintain consistency. The corpus was coded by a single author, which may bias code assignment. To mitigate this risk, a second coder independently reviewed a subset of the coded corpus, 21 workflows, including contributions with varying workflows. Discrepancies were discussed and resolved through consensus, and the codebook was refined accordingly.

The resulting codebook captured three complementary aspects of object-bound haptic authoring: the research perspective from which a contribution approached the problem, the haptic qualities intentionally being authored, and the sequence of authoring, realization, and evaluation activities that constituted each workflow. These aspects form the three dimensions of the taxonomy presented next.

5 The Object-Bound Haptic Authoring Taxonomy

Our taxonomy characterizes object-bound haptic authoring through three complementary dimensions (Figure 1). *Primary research focus* distinguishes haptics- and fabrication-oriented contributions and is coded at the paper level. *Haptic target* captures the tactile or kinesthetic qualities intentionally being authored and may receive multiple labels within a workflow. *Authoring workflow* captures the ordered sequence of digital and physical stages through which haptic behavior is specified, realized, evaluated, and refined. Both *Haptic target* and *Authoring workflow* are coded at the workflow level.

5.1 Dimension 1 — Primary research focus

Object-bound haptic authoring spans work from different disciplinary perspectives. We distinguish between **haptics-oriented** contributions, which foreground the design, authoring, understanding, or evaluation of haptic behavior, and **fabrication-oriented** contributions, which foreground the materials, structures, mechanisms, or computational methods through which such behavior is realized. The distinction concerns the research focus rather than the technology used. For example, VoxelHap [16] explicitly targets tactile and kinesthetic feedback in virtual reality, whereas LamiFold [34] primarily contributes a fabrication workflow for objects with integrated mechanisms. We determine primary research focus from the motivation, stated contributions, and evaluation of each work rather than its venue or disciplinary origin.

5.2 Dimension 2 — Haptic target

This dimension captures the haptic quality that a workflow intentionally seeks to design, reproduce, or modify. Building on classifications of object properties in haptic perception [21, 33], we distinguish five targets:

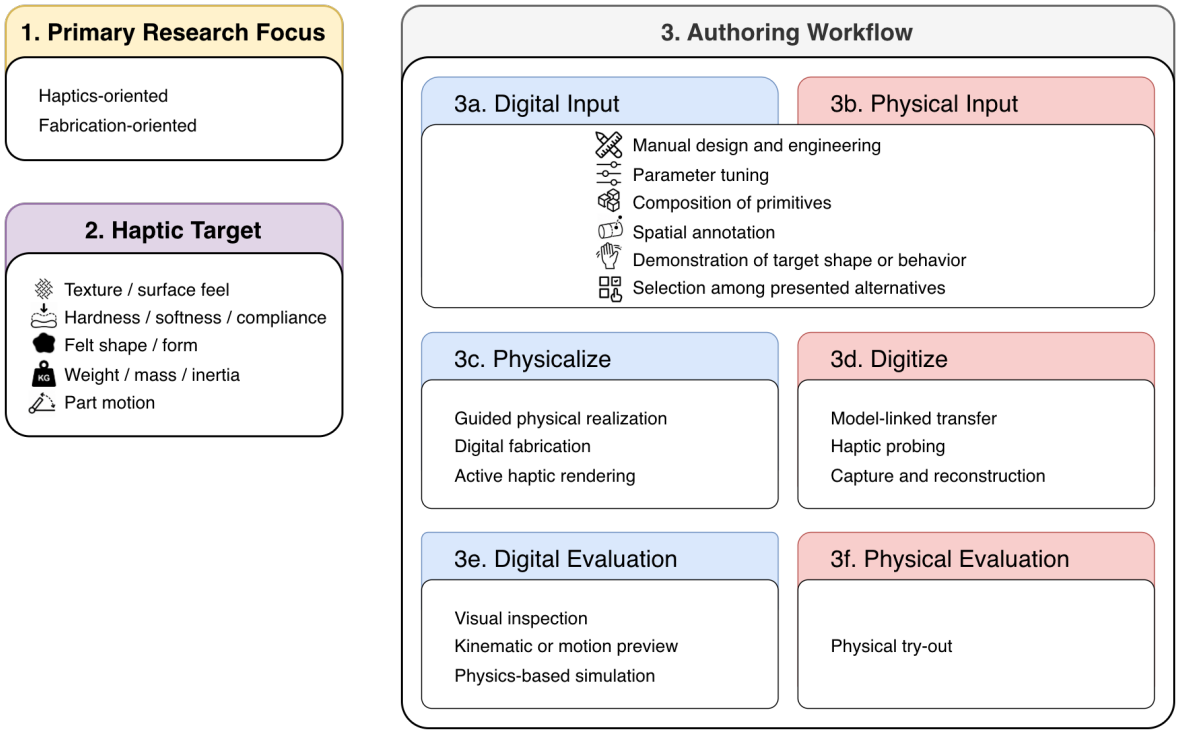


Figure 1: The object-bound haptic authoring taxonomy. It characterizes each workflow through *Primary research focus*, *Haptic target*, and *Authoring workflow*, with the latter describing how haptic behavior is specified, transferred between digital and physical representations, physically realized, and evaluated.

Texture / surface feel concerns local surface properties such as roughness, friction, patterns, or microgeometry, as in Tabby [68] and ConTextural [27].

Hardness / softness / compliance concerns deformation under applied force, including stiffness, elasticity, flexibility, and compressibility [30, 60].

Felt shape / form concerns geometry intentionally experienced through touch or physical manipulation, such as volume, contour, or graspable form [7, 89]. General geometric modelling is not sufficient. We code *Felt shape / form* only when how the geometry is experienced through touch or physical manipulation is itself an explicit design or evaluation concern.

Weight / mass / inertia concerns perceived mass properties, including weight, balance, mass distribution, and inertia [51, 71].

Part motion concerns the tactile and kinesthetic behavior of moving object parts, including motion, resistance, friction, spring behavior, detents, clicks, snaps, and end stops [49, 88].

A workflow may address multiple haptic targets. We assign a target only when it is an explicit part of the intended haptic outcome rather than an incidental consequence of another design decision. For example, Microstructures to Control Elasticity in 3D Printing [60] is coded for compliance but not texture, since only compliance is intentionally authored.

6 Dimension 3 — Authoring workflow

This dimension captures how object-bound haptic authoring unfolds across digital and physical spaces. We represent each workflow as an ordered sequence of stages. The following stages were identified: *Digital input*, *Physical input*, *Digitize*, *Physicalize*, *Digital evaluation*, and *Physical evaluation*. Together, these capture where haptic intent is specified or revised, how information moves between digital and physical representations, when a design becomes physically experienceable, and how it is evaluated. *Physicalize* denotes a transition from a digital representation to a physically experienceable form, while *Digitize* transfers haptic-relevant information from a physical representation into digital form. For example, Make it stand [51] includes *Physicalize* → *Physical evaluation*, while BrickstARt [64] moves from physical authoring through *Digitize* to subsequent digital authoring.

Unlike the preceding dimensions, stage order and repetition are meaningful. Each stage occurrence can also receive one or more labels from Dimensions 3a–3f that describe the authoring, realization, or evaluation approach used. A paper may contribute multiple workflows when different haptic targets follow substantially different authoring sequences. HapticPrint [71], for example, uses different workflows for texture, weight and compliance, which we code separately to preserve where authoring and evaluation occur.

The following subsections define each stage and its associated labels.

6.1 Dimensions 3a–3b — Digital and Physical Input

Digital and physical input capture how a designer specifies or revises the intended haptic behavior by modifying a digital or physical representation. We identify six authoring approaches that can occur in both physical and digital spaces.

Manual design and engineering develops the haptic realization largely from scratch, for example by designing geometry, materials, or mechanisms in CAD or by physically constructing them from existing components.

Parameter tuning modifies predefined variables of an existing design, such as dimensions, texture density, material distribution, tension, preload, or mass position. Parameters may expose technical values or more perceptual controls such as softer, stiffer, rougher, or smoother [71].

Composition of primitives combines reusable elements that already encode relevant geometric, material, mechanical, or haptic behavior, either digitally or physically [16, 34]. Primitives may themselves be parameterized, as in Kinergy [19], combining *parameter tuning* and *composition of primitives*.

Spatial annotation assigns a haptic property, structure, or behavior to a location or region of an existing representation rather than constructing its realization directly [18].

Demonstration of target shape or behavior specifies the intended outcome by demonstrating its motion, deformation, shape, or other behavior through digital or physical manipulation [24, 29].

Selection among presented alternatives lets the designer specify or refine an outcome by choosing among predefined, example-based, or computationally generated alternatives [7, 30, 71]. This differs from *composition of primitives*, where the designer constructs a result by combining or arranging reusable elements.

6.2 Dimension 3c — Physicalize

Physicalize captures the transition from a digital representation to a physically experienceable form. We distinguish three approaches:

Digital fabrication realizes a digital specification through computer-controlled fabrication, such as 3D printing, laser cutting, or CNC milling.

Guided physical realization manually realizes a digitally specified design using physical materials, components, or primitives, with the digital representation guiding construction or assembly. HapTwist [89], for example, computationally derives a structure that is subsequently assembled physically.

Active haptic rendering uses a programmable haptic device or actuator to physically render all or part of a digitally specified behavior. It can serve as a preview before the final object-bound artifact is realized. Interactive Material Design [81], for example, renders the mechanical response of a digital material before fabrication. It can also be part of the final artifact, where programmed actuation is combined with artifact-specific properties. In Shifty [86], for example, the mechanism and movable mass are engineered into the physical proxy, while actuation renders a changing mass distribution. Haptic-effect authoring can therefore form part of an object-bound haptic authoring workflow, either as an intermediate step or as part of the final result.

Multiple *Physicalize* labels may occur within the same workflow, for example when active haptic rendering precedes digital fabrication or fabricated parts subsequently require guided assembly.

6.3 Dimension 3d — Digitize

Digitize captures the transfer of haptic-relevant information from a physical artifact or interaction into digital form for subsequent authoring. We distinguish three approaches:

Model-linked transfer applies when information from a physical artifact or interaction is used to update an existing digital representation. This may happen indirectly, when physically evaluating an artifact informs which parameter or feature of its digital model should be changed, or directly, when changes to a physical representation are automatically reflected in a linked digital model as in tangible modeling.

Capture and reconstruction creates new digital data or representations by capturing properties of a physical artifact, for example through photography, scanning, tracking, or reconstruction. BrickStARt [64], for example, reconstructs a physically assembled brick model as digital geometry for subsequent refinement.

Haptic probing deliberately stimulates or manipulates a physical artifact and measures its haptic or mechanical response, such as texture, deformation, stiffness, friction, motion, or force response [12, 42].

6.4 Dimension 3e — Digital Evaluation

Digital evaluation captures how a designer assesses an object-bound haptic design through a digital representation. We distinguish three approaches:

Visual inspection assesses visible design properties such as geometry, surface structure, material distribution, or component configuration, including conventional CAD renderings.

Kinematic or motion preview visualizes how an artifact or its parts move or change configuration, without necessarily predicting forces or deformation.

Physics-based simulation predicts physical or mechanical behavior relevant to the intended haptic outcome, such as deformation, stiffness, force response, contact, or friction.

6.5 Dimension 3f — Physical Evaluation

Physical evaluation captures when a designer assesses the haptic behavior of a physically realized artifact. We identify one recurring approach:

Physical try-out involves directly experiencing the artifact by touching, deforming, lifting, or manipulating it. We include both explicit evaluation steps and informal handling that was not reported as evaluation but informs subsequent refinement, such as flexing a printed part and noticing that it is too stiff.

Our coding did not reveal sufficiently distinct recurring forms of physical evaluation to warrant additional labels. Across the corpus, physical evaluation predominantly takes the form of direct physical try-out, with comparatively little author-facing support for more structured or quantitative characterization of the realized haptic behavior, such as force measurements, stiffness or strength tests, friction measurements, or instrumented motion analysis. We briefly

describe how this physical evaluation is reported at the paper-level (Section 7).

6.6 Coding Authoring Workflows using Dimension 3

Combining the six stages and their labels allows us to represent complete authoring workflows. For example, Stay Tuned [49] supports digital design and parameter tuning of a bistable mechanism, digital inspection, fabrication, physical evaluation, and post-fabrication tuning. We represent this workflow as:

Digital input (*Manual design and engineering*, *Parameter tuning*) → *Digital evaluation* (*Physics-based Simulation*) → *Physicalize* (*Digital fabrication*) → *Physical evaluation* → *Physical input* (*Parameter tuning*).

Applying this representation across the corpus resulted in 56 workflows. Every stage occurrence in these workflows could be described with the labels defined above, and no additional labels were required. The complete coding is provided in Appendix A.

7 Insights from Applying the Taxonomy

Our analysis uses the 51 papers as the unit for *Primary research focus* and the 56 identified workflows for *Haptic target* and *Authoring workflow*. Within Dimension 1, 31 papers were classified as primarily having a *fabrication-oriented* and 20 as having a *haptics-oriented* contribution.

7.1 Haptic Targets

Across the 56 workflows, *Part motion* was the most common haptic target, occurring in 24/56 workflows. Its prominence may partly reflect the breadth of this category, which encompasses different types of motion, constraints, and mechanism behavior, together with the substantial body of fabrication research concerned with engineering moving mechanisms. *Felt shape / form* occurred in 18/56 workflows and *Texture / surface feel* in 15/56. In contrast, *Hardness / softness / compliance* occurred in 9/56 workflows and *Weight / mass / inertia* in 7/56. These lower frequencies suggest that compliance and mass-related properties remain comparatively underexplored as haptic effects in object-bound haptic authoring.

Because a workflow may receive more than one haptic-target label, these counts are not mutually exclusive. This occurred in 11/56 workflows, most common combination of *haptic target* that was authored within a single workflow was *Part motion* and *Felt shape / form* (5/56). Make It Stand [51], for example, exposes both shape and mass distribution as editable properties within the same authoring workflow. Overall, however, most workflows focused on a single haptic target. This is notable because object-bound haptic artifacts simultaneously exhibit properties such as shape, surface texture, compliance, weight, and mechanical behavior, which may also interact perceptually [39]. Authoring several of these haptic properties together therefore remains comparatively underexplored in state-of-the-art literature. When different haptic targets involve even slightly different authoring processes, we represent them as separate workflows; workflows with multiple targets authoring may therefore be slightly understated.

7.2 Digital and Physical Input

Digital input appears in 45/56 workflows and is dominated by *Parameter tuning* (32/45), followed by *Composition of primitives* (19/45) and *Spatial annotation* (17/45). *Manual design and engineering* (9/45) and *Demonstration of target shape or behavior* (9/45) occur less frequently, while *Selection among presented alternatives* is rare (2/45). Individual *digital input* approaches, however, still vary considerably in how they are instantiated. *Digital parameter tuning*, for example, ranges from parameters controlling characterstics of geometric mechanism, such as spring dimensions and travel in ShapeHaptics [88], to more perceptually meaningful controls such as the perceived stiffness in Ondulé [18]. Kinergy [19] illustrates how multiple *digital input* approaches can also be combined by composing predefined mechanical primitives and subsequently tuning their behavior.

Physical input occurs in 28/56 workflows and shows a different distribution. *Composition of primitives* is most common (18/28), followed by *Parameter tuning* (7/28) and *Manual design and engineering* (6/28), while the remaining approaches occur only sporadically. Physical composition typically relies on tangible building blocks, as in VoxelHap [16] and Mod2Hap [20]. This contrast reflects two common ways of authoring object-bound haptics: digital tools frequently expose editable parameters or regions of a design, while physical authoring more often proceeds by assembling or reconfiguring tangible elements.

The preferred input approaches also differ across *haptic targets* (Full overview in Appendix B). *Texture / surface feel* and *Hardness / softness / compliance* rely strongly on digital *Parameter tuning* (9/13 and 8/9 workflows respectively) and *Spatial annotation* (5/13 and 5/9). Touch-n-Go [65], for example, lets designers assign and tune texture properties over selected regions of a model. *Part motion* authoring similarly makes extensive use of digital *Parameter tuning* (16/19), followed by *Composition of primitives* (12/19), reflecting the frequent use of reusable mechanisms to construct motion behavior. Physical authoring of *part motion* is also primarily based on *Composition of primitives* (8/14).

Felt shape / form shows a different pattern. Digital input is spread relatively evenly across several approaches, including *Parameter tuning* (4/10), *Composition of primitives* (4/10), *Manual design and engineering* (3/10) and *Spatial annotation* (3/10). Physical input, in contrast, is strongly dominated by *Composition of primitives* (12/14), as in TanGi [15], VoxelHap [16], and BrickStARt [64]. This suggests that felt shape can be specified digitally through several representations, while physical authoring more often relies on directly constructing or reconfiguring tangible geometry. *Weight / mass / inertia*, by contrast, is predominantly authored digitally through *Parameter tuning* (4/7) and *Spatial annotation* (3/7), with relatively little physical input. HapticPrint [71], for example, allows designers to assign different weight properties to regions of a digital model, which are subsequently realized through fill material.

Digital and physical input can also complement one another within the same workflow. ReCompFig [82] first lets designers specify kinematic modes and degrees of freedom digitally. After fabrication, the mechanism remains physically adjustable by tightening cables to selectively constrain these degrees of freedom. The

workflow therefore combines digital specification with subsequent physical tuning of the realized mechanism.

7.3 Physicalize and Digitize

The *Physicalize* and *Digitize* stages show a pronounced asymmetry. *Physicalize* occurs in 53/56 workflows, whereas *Digitize* (15/56) is much less common. Object-bound haptic authoring therefore predominantly moves from digital representations toward physical realization, while transferring information from physical artifacts back into digital form occurs far less frequently.

Separating workflows by their paper's primary research focus shows that this asymmetry also persists within haptics-oriented research. Among these workflows, *Physicalize* occurs in 22/25, whereas *Digitize* occurs in 10/25. The difference is more pronounced among fabrication-oriented workflows, where *Physicalize* occurs in 31/31 and *Digitize* in only 5/31. The asymmetry is therefore present in both subsets, rather than being limited to fabrication-oriented research.

Our review cannot establish why the asymmetry exists, but two factors plausibly contribute. First, our inclusion criteria require an artifact-bound outcome and most of the corpus is fabrication-oriented, so digital-to-physical transitions may be more common given the definitions and inclusion criteria of our review. Second, *Haptic probing* appears uncommon, with *Haptic probing* being the least common form of *Digitize* (3/15).

Physicalize is predominantly realized through *Digital fabrication* (44/53), while *Guided physical realization* (13/53) and *Active haptic rendering* (6/53) occur less frequently. This reflects the strong role of digitally specified geometry, material structures, and mechanisms in the corpus. Different forms of physicalization can also complement one another. FabriClick [17], for example, combines digitally fabricated textile components with guided manual alignment and assembly. *Active haptic rendering* is comparatively rare and instead uses programmable haptic devices to make aspects of a digitally specified behavior physically experienceable before or without fabricating the complete artifact.

Among 15 workflows containing *Digitize*, *Capture and reconstruction* is most common (9/15), followed by *Model-linked transfer* (6/15) and *Haptic probing* (3/15). Digitization serves two broad roles. It can provide an initial digital representation of a physical reference, as in TactStyle [14], or connect physical authoring back to subsequent digital stages, as in Makers' Marks [56]. Notably, most digitization workflows capture geometry, configuration, or other information whose relation to the haptic outcome is already known. Directly measuring haptic or mechanical behavior through *Haptic probing* is uncommon. This suggests that closing the loop from physically experienced haptic behavior back to a digital representation remains comparatively underexplored in object-bound haptic authoring.

Some differences also emerge across *haptic targets* (full details in Appendix C). *Texture / surface feel* is almost exclusively physicalized through *Digital fabrication* (15/15), with only one workflow additionally using *Guided physical realization* and none using *Active haptic rendering*. In contrast, digitization of texture is comparatively diverse, with *Capture and reconstruction* occurring in 4/6 workflows, *Haptic probing* in 2/6, and *Model-linked transfer* in 1/6. Capturing Tactile Properties [12] is notable in that it directly probes real surfaces to capture microgeometry for subsequent digital reproduction. Haptic Target *Felt shape / form* shows a broader range of transitions. It is physicalized through *Digital fabrication* (10/15), *Guided physical realization* (5/15), and *Active haptic rendering* (2/15). Digitization is also more common for felt shape, particularly through *Capture and reconstruction* (5/7) and *Model-linked transfer* (3/7). VoxelHap [16], for example, continuously tracks the configuration of physical voxels in a corresponding digital model, while PneuSeries [8] illustrates the less common use of *Active haptic rendering* to physically instantiate a digitally specified shape.

By contrast, *Digitize* is uncommon for *Hardness / softness / compliance*, *Weight / mass / inertia*, and *Part motion*. For compliance, only one workflow uses *Digitize*, through *Model-linked transfer* in Reconfigurable Elastic Metamaterials [84]. For weight, only 1 workflows use *Digitize*, through *Capture and reconstruction* in BrickStARt [64]. For part motion, *Model-linked transfer*, *Capture and reconstruction* and *Haptic probing* each occur in only 1/2 workflows. Makers' Marks [56], for example, uses *Capture and reconstruction* to capture annotated functional elements such as hinges and reconstructs them digitally. VoxelHap [16] uses *Haptic Probing* to record interaction-induced vibrations from real-world objects using a contact vibration microphone. *Model-linked transfer*, also for VoxelHap [16] captures the assembled Voxel configuration, allowing the placement of RotationVoxels to directly define rotational degrees of freedom in the corresponding digital model. These low frequencies are notable because these properties are, however, routinely physically experienced after realization, yet the resulting physical behavior is rarely transferred back into digital form. Overall, these observations suggest that current object-bound haptic authoring provides extensive support for turning digital designs into physical artifacts, but substantially less support for capturing the resulting haptic behavior and feeding it back into subsequent digital authoring.

7.4 Digital and Physical Evaluation

Evaluation is prevalent throughout the corpus. *Digital evaluation* occurs in 53/56 workflows, while *Physical evaluation* occurs in all 56. The latter partly follows from the object-bound scope of the corpus, since each workflow ultimately produces a physically experienceable haptic outcome and we also code handling of the resulting artifact as *Physical evaluation*. Digital evaluation most commonly relies on *Visual inspection* (37/53), while *Kinematic or motion preview* (12/53) and *Physics-based simulation* (4/53) are considerably less frequent (full overview in Appendix D).

Although *Physical evaluation* occurs in all 56 workflows, this does not imply that every paper explicitly describes it as an authoring step. To examine this, we separately assessed how physical evaluation is reported across the 51 papers. Physical assessment is explicitly reported in 43/51 papers, while 22/51 report objective physical measurements. The latter include laboratory characterization and research experiments, which may validate research contributions without necessarily being author-facing stages in the resulting workflow. However, even when physical assessment is not explicitly reported, users of the workflow can still physically

evaluate their artifacts and use their observations to refine subsequent designs. Explicit transfers of information from physical artifacts back into digital models are coded separately as *Model-linked transfer*.

Visual inspection occurs across all haptic targets, but what can be assessed visually differs considerably. It is particularly common for *Texture / surface feel* (14/15) and *Felt shape / form* (15/15), where surface structure or geometry can often be inspected directly. *Part motion* is also visually inspected in 7/21 workflows, typically by examining the geometry or configuration that enables the motion rather than the resulting haptic behavior itself [18, 65]. It also occurs for *Hardness / softness / compliance* (8/9) and *Weight / mass / inertia* (7/7), but here the visualization generally exposes design features that determine the eventual haptic outcome, such as material structure or mass distribution, rather than the felt property itself. Visual inspection therefore provides broad support for evaluating object-bound haptic designs, but often only indirectly communicates the resulting haptic experience.

More behavior-specific forms of digital evaluation are concentrated around *Part motion*. *Kinematic or motion preview* occurs in 11/21 *Part motion* workflows and *Physics-based simulation* in 3/21. Kinergy [19], for example, lets designers preview the motion produced by embedded kinetic units before fabrication, while Metamaterial Mechanisms [22] simulates the mechanical response of compliant cell structures. *Texture / surface feel* uses *Kinematic or motion preview* once (1/15): Metamaterial Textures [23] previews how the surface texture changes as the structure compresses. *Physics-based simulation* occurs only once for *Hardness / softness / compliance* (1/9), in Interactive Material Design [81], where deformation behavior is simulated interactively during authoring. Neither motion preview nor physics-based simulation occurs for *Felt shape / form* or *Weight / mass / inertia* in our corpus.

Physical evaluation, by contrast, occurs for every haptic target and directly exposes the resulting haptic behavior through interaction with the artifact. Depending on the target, this may involve rubbing a surface, pressing a compliant structure, grasping or lifting an object, or manipulating a moving part. Our coding did not reveal recurring forms of physical evaluation beyond this direct physical experience. Taken together, these findings show that final haptic outcomes are typically assessed through direct physical try-out, with little support for more structured or quantitative physical characterization. Digital evaluation, meanwhile, predominantly supports inspection of the underlying design and only occasionally predicts the resulting haptic behavior before physical realization.

7.5 Recurring Workflow Structures

Examining individual stages reveals which authoring activities are supported, but not how these activities are combined into complete workflows. We therefore compare the ordered stage sequences across the corpus and identify recurring higher-level workflow structures. These structures summarize recognizable ways of moving from haptic intent to a physically experienceable result. They are not additional taxonomy labels and are not necessarily mutually exclusive, since a single system may support more than one such workflow.

7.5.1 Digitally Authored Fabrication. is the most prevalent structure (39/56 workflows). The most popular *haptic targets* authored through this workflow are *part-motion* (18/39) followed by *texture* (12/39). Here, the haptic behavior is specified and evaluated digitally before the design is physically realized through digital fabrication and evaluated through touch. The characteristic sequence is therefore *Digital input* → *Digital evaluation* → *Physicalize* (*Digital fabrication*) → *Physical evaluation*. This structure occurs across different *haptic targets*. X-Hair [79], for example, digitally specifies hair-like surface *textures* before 3D printing, while FlexHaptics [40] uses a similar overall workflow to author *part motion* mechanisms.

7.5.2 Tangible Modeling. occurs in 15/56 workflows and instead uses a physical representation as the primary authoring medium. The most popular *haptic targets* authored through this workflow are *Felt shape / form* (10/15) and *part motion* (8/15). These workflows center on *Physical input (composition of primitives)* → *Physical evaluation*, allowing designers to construct or reconfigure a physical model and directly experience the resulting haptic behavior. TanGi [15], for example, allows designers to compose reusable physical primitives into tangible proxies that can be immediately handled and evaluated. VoxelHap [16] extends this approach with modular components that expose several haptic properties.

7.5.3 Tangible-to-Digital Fabrication. is much less common (2/56 workflows) and only occurred when authoring *Felt shape / form* and *Weight / mass / inertia*. Here, a design is first authored and evaluated physically, then transferred into a digital representation that is subsequently used to produce a fabricated realization. StrutModeling [35] illustrates this structure: designers construct and manipulate a physical strut model while its configuration is captured digitally, after which the resulting digital representation can be fabricated. Importantly, this structure is not equivalent to simply combining tangible modeling with digital fabrication. MagnetoHaptics [47], for example, supports the digital design and fabrication of magnet-embedded building blocks. The user then physically combines and tests these building blocks to explore different haptic configurations. This workflow does not conform to the tangible-to-digital fabrication workflow but is a combination of *Tangible Modeling* and *Digitally Authored Fabrication*.

7.5.4 Patterns for Faster Authoring Iterations. Beyond these broader workflow structures, we identify two recurring patterns that shorten the authoring iteration cycle: *digital preview iteration* and *post-fabrication tuning*. Digital preview iteration, observed in 15/56 workflows, follows *Digital input* → *Digital evaluation* → *Digital input*, where evaluation relies on *Kinematic or motion preview* or *Physics-based simulation*. This allows designers to iteratively modify and evaluate a design before physical realization. Post-fabrication tuning, observed in 16/56 workflows, follows *Physicalize* → *Physical evaluation* → *Physical input* → *Physical evaluation*, allowing the realized artifact to be adjusted and reevaluated without starting another, often time-consuming, fabrication cycle. Both patterns therefore support refinement within the same representation space and reduce the need to repeatedly transition between digital and physical authoring. HapLinkage [36], for example, supports repeated physical fine-tuning of linkage rod lengths after fabrication,

while Kinergy [19] allows designers to modify a digital mechanism and preview its resulting motion before fabrication.

8 A Unified Model of Object-Bound Haptic Authoring

The recurring workflow structures identified in Section 7.5 can be understood as different paths through a common authoring model. Rather than prescribing a single workflow, Figure 2 synthesizes the stage transitions observed across the corpus and shows how object-bound haptic authoring moves between digital and physical representations during specification, realization, evaluation, and refinement. All transitions identified in the coded workflows (Appendix A) are represented in the model.

The model contains two primary authoring loops. In digital space, *Digital input* and *Digital evaluation* support repeated modification and evaluation before physical realization. In physical space, *Physical input* and *Physical evaluation* support adjustment and immediate experience of the realized artifact. The digital preview iteration and post-fabrication tuning patterns identified in Section 7.5 are instances of these loops.

Physicalize and *Digitize* connect the two spaces. *Physicalize* makes a digital design physically experienceable through *digital fabrication*, *guided physical realization*, or *active haptic rendering*, while *Digitize* transfers haptic-relevant information from physical experience into digital form for subsequent authoring. Information may also move directly between spaces without either transition. For example, *Digital evaluation* may inform manual adjustment of an existing artifact, producing a direct transition to *Physical input* without instantiating the digital design itself.

The recurring workflow structures follow different paths through this model. *Digitally authored fabrication* primarily follows the digital loop before *Physicalize* and physical evaluation. *Tangible modeling* remains largely within the physical loop, while *tangible-to-digital* fabrication moves from physical authoring through *Digitize* into digital authoring and subsequently back through *Physicalize*. The model therefore provides a common representation for technically different workflows ranging from tangible modeling and manual engineering to CAD-based authoring, digital fabrication, and haptic preview.

9 Discussion and Future Work

Our review reveals a field that provides substantial support for engineering object-bound haptic behavior, but considerably less support for expressing haptic intent, anticipating the resulting experience, and incorporating what is learned from the realized artifact into subsequent authoring. We discuss these gaps below and identify opportunities for more integrated object-bound haptic authoring.

9.1 From Engineering Artifact Properties to Authoring Haptic Experience

Object-bound haptic authoring has largely developed from fabrication, computational design, and mechanism engineering. Most papers in our corpus are fabrication-oriented, and *Digitally Authored Fabrication* is the dominant recurring workflow. Correspondingly, digital authoring commonly exposes geometry, material structures, mechanism parameters, or fabrication parameters that indirectly determine what will ultimately be felt.

This creates a gap between haptic intent and the representations through which it is authored. *Parameter tuning* dominates digital input, while approaches based on demonstrating a desired behavior or selecting among perceptually meaningful alternatives remain comparatively uncommon. Future tools could expose higher-level haptic properties more directly, for example allowing designers to specify that a mechanism should feel stiffer, more pronounced, or smoother while computational methods translate these intentions into appropriate artifact-specific parameters.

9.2 Closing the Digital–Physical Authoring Loop

Our findings show a strong asymmetry between moving from digital representations to physical artifacts and bringing information from realized artifacts back into digital authoring. *Physicalize* occurs in almost every workflow, whereas *Digitize* is much less common. Even when digitization occurs, it predominantly captures geometry or physical configuration rather than directly characterizing the resulting haptic behavior.

This is particularly limiting because object-bound haptic behavior often becomes fully apparent only after physical realization. The resulting artifact should therefore be considered not only an output of the authoring process, but also an important source of information for subsequent iterations. Future systems could capture properties such as force response, stiffness, friction, deformation, or mass distribution and associate them with the corresponding digital model. Such information could help designers understand differences between intended and realized behavior and inform subsequent design iterations. Future work could also extend the review to industrial engineering practice using the terms mentioned.

The unified model can also serve as a lens for considering how existing workflows might be extended with additional forms of authoring support. StrutModeling [35], for example, transfers physical modifications to a digital representation. A future extension could additionally analyse that digital model and provide concrete guidance for modifying the physical configuration, thereby supporting a more tightly coupled digital–physical authoring loop.

9.3 Supporting Evaluation Before and After Physical Realization

A related limitation concerns how designers evaluate haptic behavior. Although *Digital evaluation* is widespread, it predominantly consists of visual inspection. Designers can therefore inspect the geometry, structure, or material distribution responsible for a haptic outcome, but only rarely receive a prediction of the resulting haptic behavior. Kinematic preview and physics-based simulation provide richer feedback, but occur comparatively infrequently.

At the physical side of the workflow, every artifact is evaluated through direct physical experience, yet this evaluation is predominantly informal. Our coding revealed little recurring authoring support for systematically characterizing the realized behavior. Future systems could therefore strengthen evaluation on both sides of physical realization. Simulation or active haptic preview could provide earlier feedback on expected behavior, while instrumented

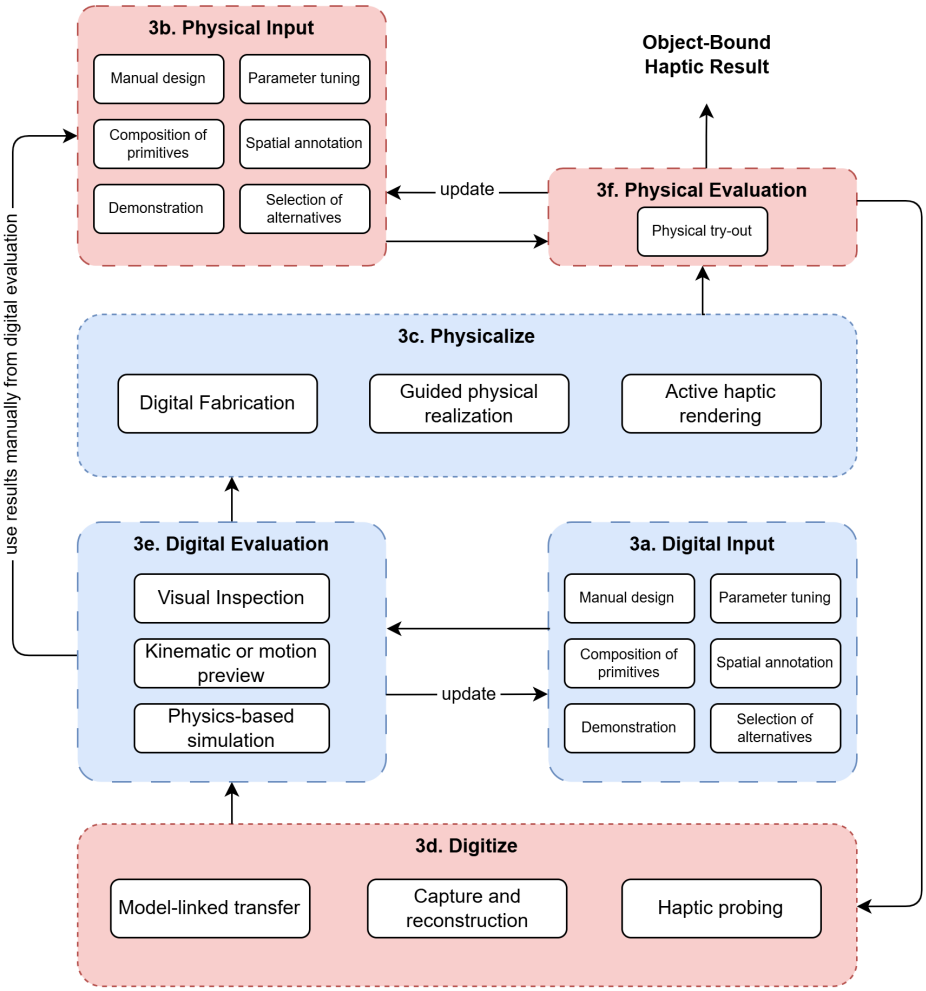


Figure 2: A unified model of object-bound haptic authoring synthesized from the workflows in our corpus. Arrows represent observed transitions between stages rather than a prescribed sequence. Individual workflows traverse only a subset of the model.

measurements could complement direct physical try-out after fabrication.

Active haptic rendering already demonstrates one possible bridge, but occurs in only a small subset of workflows. Programmable haptic devices, reconfigurable interfaces, or other intermediate physical representations could allow designers to experience selected aspects of a design before committing to its final fabrication. Such previews need not reproduce the complete artifact to be useful. Their purpose could instead be to expose the haptic properties most relevant to the current design decision.

9.4 Toward More Integrated Haptic Authoring

Current workflows also tend to address individual haptic qualities in isolation. Only a minority intentionally author multiple haptic targets, even though real artifacts simultaneously exhibit shape, texture, compliance, weight, and mechanical behavior. Future authoring environments could make dependencies between these properties more explicit and help designers reason about trade-offs when modifying one property affects several aspects of the resulting experience.

Several of these opportunities also suggest closer integration with haptic-effect authoring. Haptic-effect authoring has developed methods for rapid replay, perceptually meaningful representations, reusable effects, and programmable rendering. Object-bound authoring contributes complementary strengths in artifact-specific geometry, materials, mechanisms, fabrication, and post-fabrication refinement. Future systems could combine these approaches, allowing designers to rapidly specify and preview intended behavior before translating it into a physically realized artifact and subsequently refining that artifact based on physical experience.

More broadly, the taxonomy and unified model provide a way to reason about where an authoring system provides support and where transitions remain unsupported. They may also offer a basis for comparing future systems at the workflow level, considering not only whether a desired haptic outcome can be produced, but also where iteration occurs, how readily alternatives can be explored, and how effectively information from one iteration informs the next.

10 Conclusion

We introduced *object-bound haptics* as a framing for tactile and kinesthetic behavior that is intentionally engineered through the physical properties of an artifact. Bringing together work across haptics, fabrication, computational design, and engineering shows that this is already a substantial authoring space, even though it has rarely been treated as such. This framing highlights how the physical attributes of artifacts can be intentionally shaped to support desired tactile and kinesthetic experiences.

Our analysis suggests a field that is strong at making haptic behavior physical, but much less mature at making physical experience computationally accessible during authoring. Designers can readily move from digital models to fabricated artifacts, yet have comparatively limited support for predicting how these artifacts will feel, characterizing the realized behavior, or feeding that experience back into subsequent design. We hope the taxonomy and unified model provide a common language for studying these workflows and for developing authoring tools that more tightly connect haptic intent, physical realization, and iterative refinement.

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A Complete Workflow Coding



Figure 3: Complete coding of the 56 object-bound haptic authoring workflows in our corpus (part 1).



Figure 4: Complete coding of the 56 object-bound haptic authoring workflows in our corpus (part 2).

B Haptic Targets by Digital and Physical Input Approaches

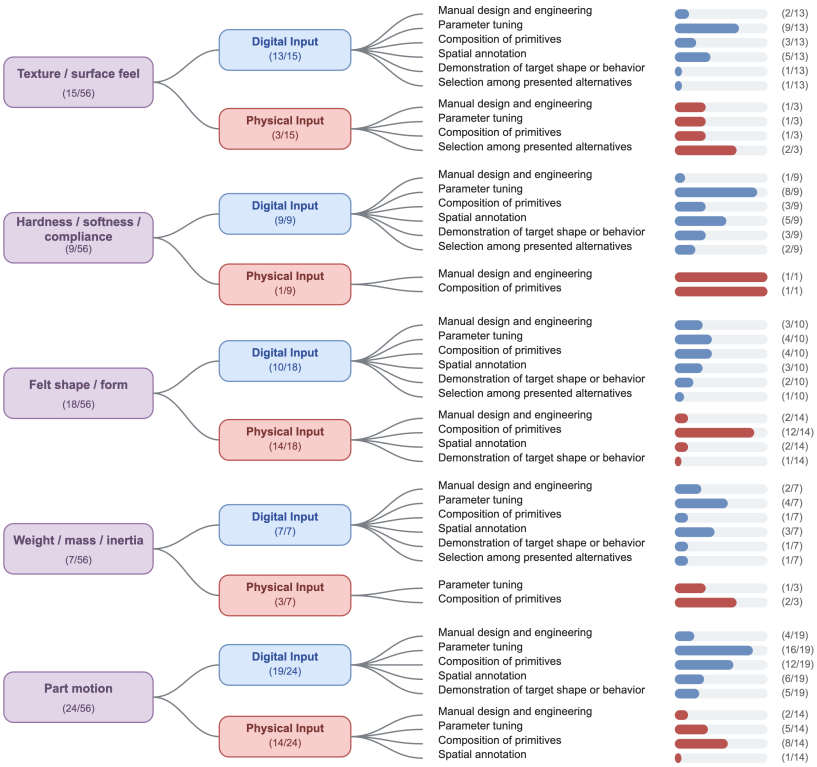


Figure 5: Digital and physical input approaches across haptic targets.

C Haptic Targets by Physicalize and Digitize Approaches

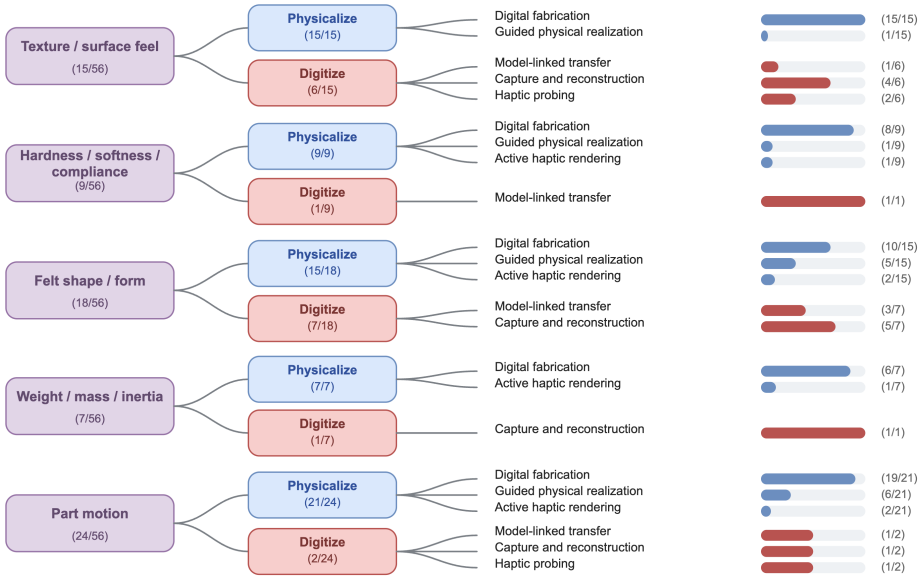


Figure 6: Physicalize and Digitize approaches across haptic targets.

D Haptic Targets by Digital and Physical Evaluation Approaches

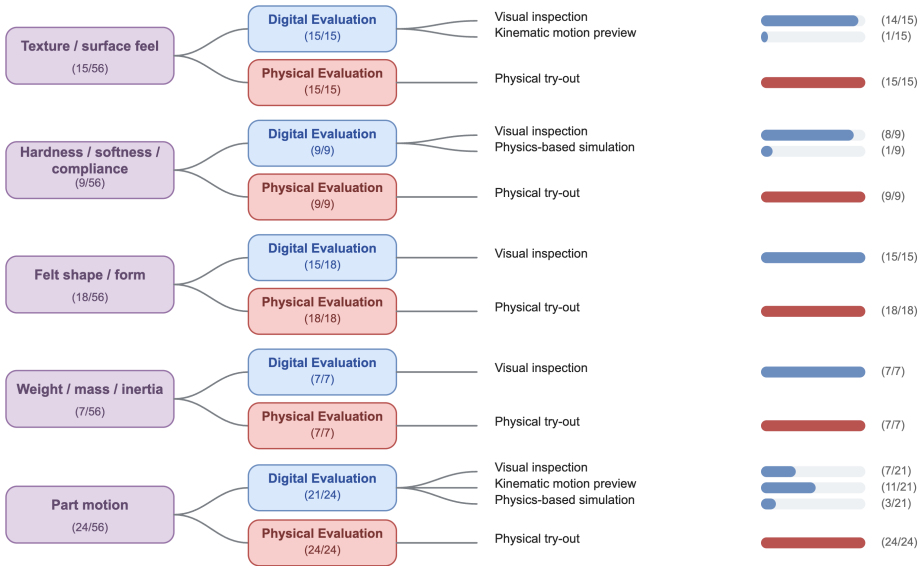


Figure 7: Digital and physical evaluation approaches across haptic targets.